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Ultimate strength of stiffened plates with pitting corrosion

Ahmad Rahbar-Ranji, Nabi Niamir and Arvin Zarookian

Department of Ocean Engineering, Amirkabir University of Technology, Tehran, Iran

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ABSTRACT: *Predicting residual strength of corroded plates is of crucial importance for service life estimation of aged structures. A series of nonlinear finite element method is employed for ultimate strength analysis of stiffened plates with pitting corrosion. Influential parameters, including plate thickness, type and size of stiffeners, pit depth and degree of pitting are varied and more than 208 finite element models are analyzed. It is found that ultimate strength is reduced by increasing pit depth to thickness ratio. Thin and intermediate plates have minimum and maximum reduction of ultimate strength with stronger stiffeners, respectively. In weak stiffener, reduction of ultimate strength in thin and intermediate plates depends on DOP. Reduction of ultimate strength in thick plates depends on thickness of plate and DOP. For intermediate plates, reduction for all stiffeners regardless of shape and size are the same.*

KEY WORDS: Stiffened-plate; Ultimate strength; Pitting Corrosion; Finite element method.

NOMENCLATURE

a	length of plate	t_f	thickness of flange of stiffener
b	width of plate	$W_{opl}(x,y)$	plate initial deflection, mm
b_f	flange width of stiffener	$W_{os}(x)$	column-type initial deflection of stiffeners
E	Young's modulus of the material	$W_{ot}(x,z)$	Side-ways initial deflection of stiffeners
h_w	web height of stiffener	α_0	plate maximum initial deflection
R	ultimate strength reduction factor		variability parameter
	of cracked stiffened plate	β	plate slenderness ratio
t	thickness of plate	ε_Y	yield Strain of the material
t_w	web thickness of stiffener	σ_Y	yield stress of the material

INTRODUCTION

Corrosion is inevitable in steel structures in marine environments. Predicting residual strength of corroded structures is of crucial importance for health monitoring and repair policy. Residual strength analysis of corroded plates was the subject of many researches in the past years. Chapkis (1967) was the first who has studied the influence of pitting corrosion on ultimate strength of steel plates and has introduced the concept of equivalent thickness for pitted plates. Paik et al. (2003; 2004) have

Corresponding author: *Ahmad Rahbar-Ranji*, e-mail: *rahbar@aut.ac.ir*

studied ultimate strength of plate elements with pit corrosion under compressive and shear loading. A series of actual test for plates with pit wastage was carried-out by Nakai et al. (2004; 2005). Ok et al. (2007) have studied ultimate strength reduction in pitted plates. Rahbar-Ranji (2012) was the first who has studied ultimate strength of corroded plates with irregular random surfaces based on proposed power spectrum of geometry of corroded surfaces (Rahbar-Ranji, 2001) using Finite Element Method (FEM). He has concluded that uniform thickness assumption for general type of corrosion could lead up-to five percent overestimation. Rahbar-Ranji (2013; 2014) has also used irregular random surfaces to study elastic buckling strength of corroded plates and has concluded that one-sided and both-sided corroded plates have almost the same strength reduction and using shell element or solid element for geometry of corroded plates yield almost the same results. Eslami and Rahbar-Ranji (2014) have studied dynamic strength of pitted plates under blast load.

A survey of the literature (Yikun et al., 2014) shows that, in spite of many research works concerning ultimate strength of corroded plates and stiffened plates, ultimate strength of stiffened plates with pitting type of corrosion has not been previously studied. It is the main aim of present work to determine residual ultimate strength of stiffened plates with pit wastage. Plate thickness, type and size of stiffeners, pit depth and degree of pitting are varied and 208 FE models of pitted stiffened plates are analyzed.

FINITE ELEMENT MODELING OF PITTED STIFFENED-PLATE

Stiffened plates are the main structural components of ship and offshore structures which consist of thin plates stiffened by relatively weak, uni-directional stiffeners and strong girders (Fig. 1). The accuracy of ultimate strength analysis of stiffened plates using FEM highly depends on appropriate boundary conditions and the extent of the model. Among different FE models which are proposed by researchers, triple bay-triple span model of Yao et al. (1998) which is easy to generate and yields accurate results is used in this study (Fig. 1).

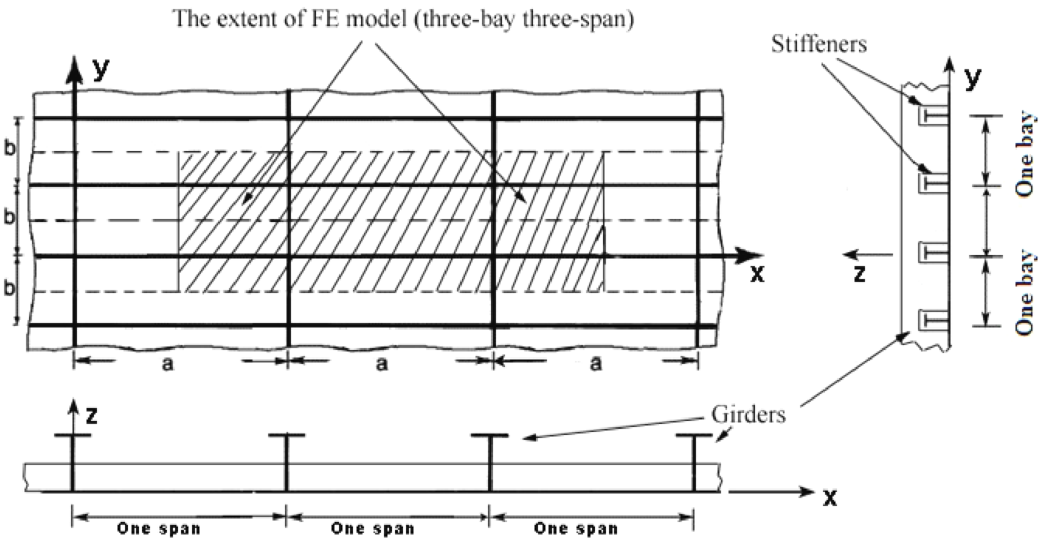


Fig. 1 Definition of stiffened plate, coordinate system and three-bay three-span model of FE (Yao et al., 1998).

Fig. 2 shows the extent of FE model and applied boundary conditions (Yao et al., 1998). At both longitudinal and transverse edges of the model periodical continuous condition is imposed. Considering the continuity of the plate, in-plane displacement of the edges in their perpendicular directions is assumed to be uniform. Transverse girders are not modeled and their influences have been considered by constraining deflection of the plate and stiffener along the lines of transverse girders in vertical and lateral directions, respectively (Paik et al., 2008). Uniform compression is applied at the both transverse edges.

Material used in this study is structural steel with bi-linear stress-strain relationship. Yield stress is assumed equal to 313.6 *MPa*, Young's modulus 205.8 *GPa*, Poisson's ratio 0.3, while the strain hardening rate has been considered as E/65.

Initial imperfections in steel structures induced by different fabrication processes such as cutting and welding are unavoidable. Among them residual stress and initial deflection are the most common initial imperfections. In this study, while the effect of residual stress has not been taken into account, different types of initial deflections are considered as explained in the following sections.

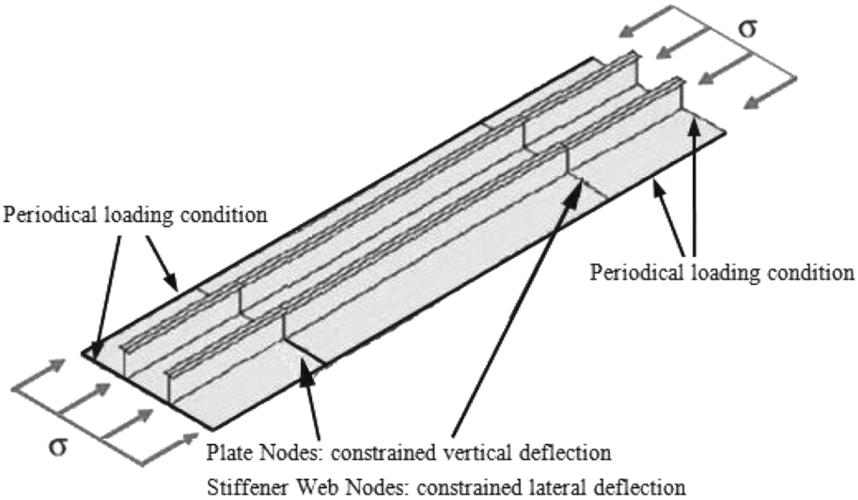
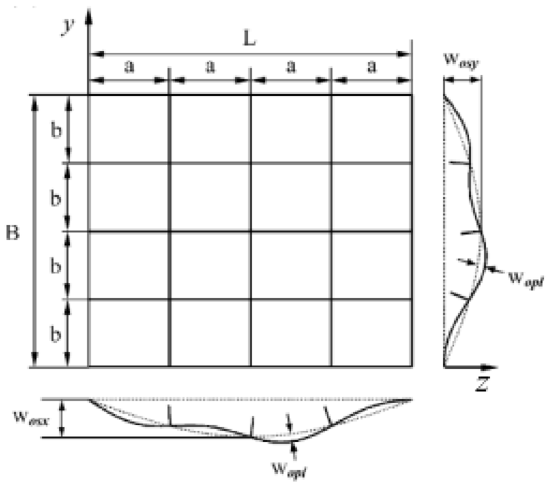


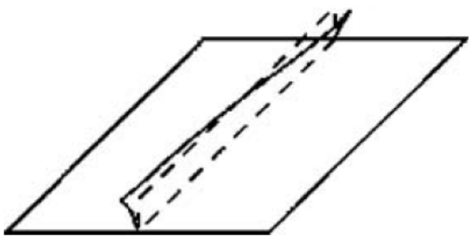
Fig. 2 Applied boundary conditions on the FE model.

Initial deflection of plate between stiffeners



(a) Plate initial deflection, W_{opl}, and column-type initial deflection of stiffeners, W_{os}, (Paik and Kim, 2002).

(b) Variability of the maximum initial deflection (α_0) in adjacent bays and spans (Yao et al., 1998).



(c) Side-ways initial deflection of stiffeners.

(d) Column-type initial deflection of stiffeners.

Fig. 3 Different types of initial deflection.

Stiffened plate between two adjacent longitudinal stiffeners and transverse girders deforms in the following form (Fig. 3(a)) (Paik and Kim, 2002):

$$W_{opl}(x,y) = 0.05\alpha_0 \beta^2 t \sin\left(\frac{3\pi x}{a}\right)\sin\left(\frac{\pi y}{b}\right) \tag{1}$$

where α_0 is a parameter accounted for variability of the maximum deflection from bay-to-bay and from span-to-span, a is the length of plate, b is the breadth of plate and β is the slenderness ratio of the plate which is defined as follows:

$$\beta = \frac{b}{t}\sqrt{\frac{\sigma_{YP}}{E}} \tag{2}$$

where t is the thickness of plate, E is Young's modulus, and σ_{YP} is yield stress of material. Fig. 3(b) shows the values of α_0 for maximum initial deflections in adjacent panels (Yao et al., 1998).

Column-type initial deflection of stiffeners

Stiffeners could have initial deflection in the form of column buckling as follows (Yao et al., 1998) (Fig. 3(a) and 3(d)):

$$W_{os}(x) = 0.001a\sin\left(\frac{\pi x}{a}\right) \tag{3}$$

Side-ways initial deflection of stiffeners

Side-ways angular rotation of stiffener about junction point of web to attached plate is assumed as follows (Yao et al., 1998) (Fig. 3(c)):

$$W_{ot}(x,z) = 0.001\frac{a}{h_W} z\sin\left(\frac{\pi x}{a}\right) \tag{4}$$

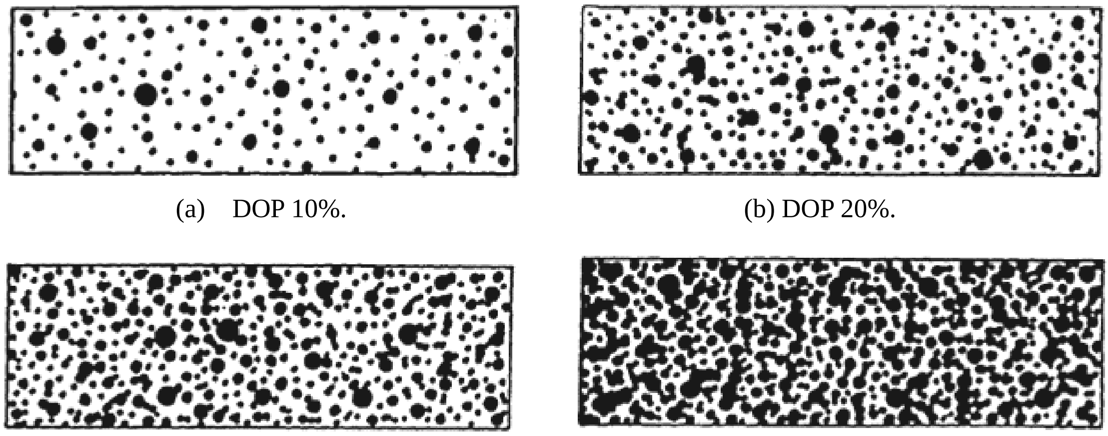
where h_w is the stiffener's web height.

WORKED OUT EXAMPLES AND DISCUSSIONS

Pitting is a localized corrosion in the form of deep holes and each pit has its own unique shape and depth. Depending on environment-metal system, different types of corrosion patterns can be expected. As a common practice, instead of modeling the individual pits, a group of pit damage in the vicinity of each other, are modeled together with a rectangular or circular shape (Ok et al., 2007; Paik et al., 2003; 2004). Usually, the scale of pitting damages is expressed by Degree of Pitting (DOP) which is defined as the ratio of the corroded area over entire plate area as follows:

$$DOP = \frac{1}{ab}\sum_{i=1}^{n} A_{pi} \times 100(\%) \tag{5}$$

where A_{pi} is the area of each individual pit, n is the total number of pits and a and b are the plate dimensions. Fig. 4 shows different pitting distribution patterns in an oil tanker plate with DOP equal to 10%, 20%, 30%, 40% and 50% (TSCF, 1993).



(a) DOP 10%.

(b) DOP 20%.

(c) DOP 30%.

(d) DOP 50%.

Fig. 4 Pitting distribution patterns (TSCF, 1993).

Strength analysis of a pitted corroded plate is evaluated only on the basis of numerical analysis with FEM. In this study, ANSYS code (version *11)* has been used to determine ultimate strength of pitted stiffened-plate. Pitted corroded plates can be modeled by using shell or solid elements. Though using solid elements is more realistic, however the generated FE model would have a large number of degree of freedom which is not appropriate for non-linear FE analysis. Besides Rahbar-Ranji (2013) has shown that using solid elements and shell elements for buckling analysis of corroded plates yield the same results. Only pitting corrosion at one side of plate, at the same side as stiffeners, has been considered and eventual pitting corrosion of stiffeners has not been considered.

Plate dimensions are assumed as 2400×800 *mm*, thickness of plate varies from 10 to 20 *mm*, and two types of stiffener with different cross sections are considered (Table 1). These stiffeners are chosen in such a way that cross section of each type to be the same. FE model of one-sided pitted corroded stiffened plates are generated using shell elements, pits are modeled as 8×8 mm squares with reduced thickness and multi-layered thickness feature of SHELL181 element is employed to model variable thickness at different nodes. Fig. 5 shows finite element model of a stiffened plate with pitting corrosion.

Table 1 Different types of stiffener considered in this study.

Type	Designation	h_w (*mm*)	t_w (*mm*)	b_f (*mm*)	t_f (*mm*)
One	F1 (flat-bar)	150	17	-	-
	T1 (tee-bar)	150	9	90	12
Two	F2 (flat-bar)	250	19	-	-
	T2 (tee-bar)	250	10	100	15

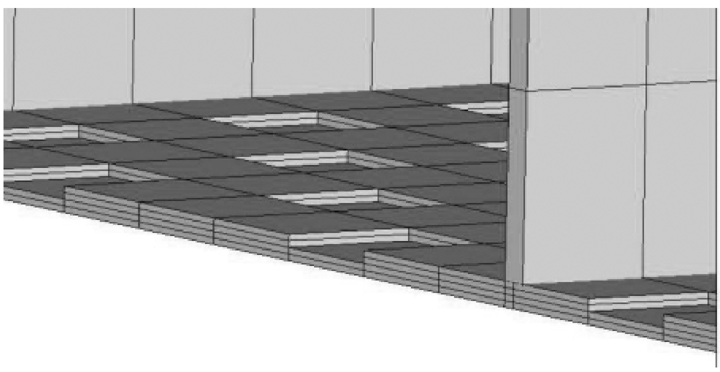
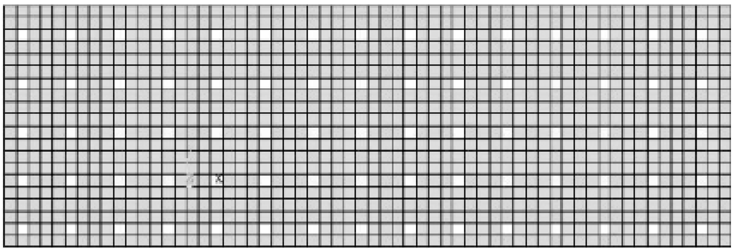
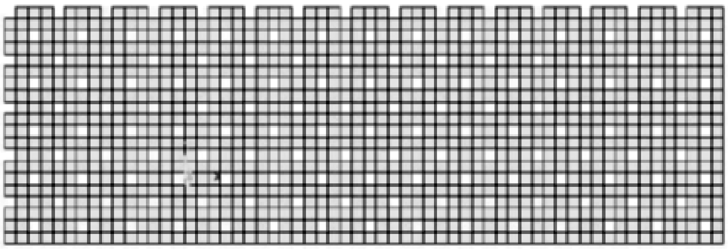


Fig. 5 FE model of pitted corroded stiffened plate in a corroded stiffened plate.

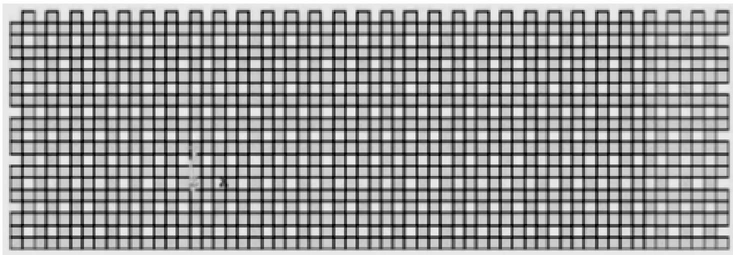
Uniform pits distribution with DOP equal to 6.25%, 12.5%, 25% and 50% (Fig. 6) with depth-to-thickness ratio equal of 25%, 50% and 75% are assumed. Totally, 208 models of pitted stiffened-plate characteristics have been analyzed. Table 2 summarizes different geometrical parameters and their ranges.



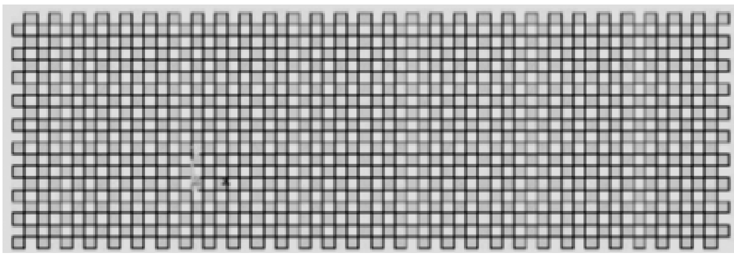
(a) DOP 6.25%.



(b) DOP 12.5%.



(c) DOP 25%.



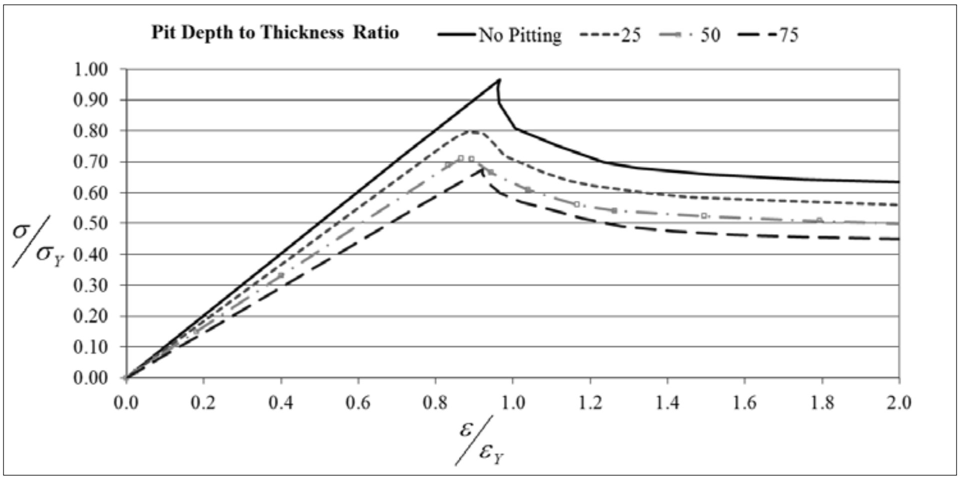
(d) DOP 50%.

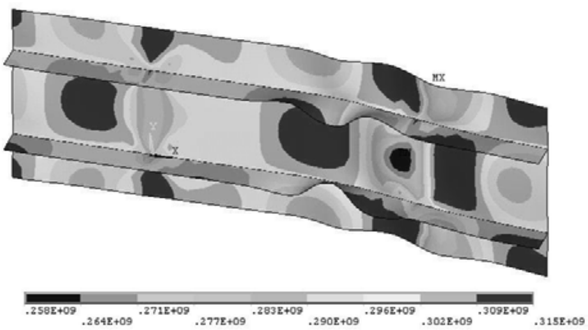
Fig. 6 Pits distribution considered in this study.

Table 2 Geometrical parameters of FE models and their values.

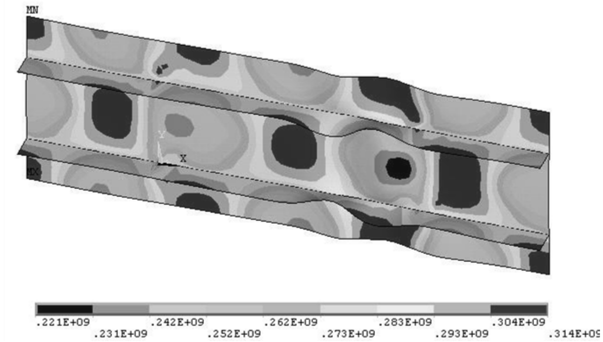
Description	Values
Plate thickness	10, 12.5, 15, 17.5, 20
Type of stiffener	See Table 1
Ratio of depth-to-thickness	25%, 50%, 75%
DOP	6.25%, 12.5%, 25%, 50%

Figs. 7 and 8 show stress-strain diagram and ultimate strength deformation with von-Misses stress distribution corresponding to ultimate strength for a 15 *mm* stiffened plate, type 2 stiffener, DOP 50% and different ratio of depth-to-thickness. As can be seen, regardless of shape of stiffener, ultimate strength is reduced by increasing depth-to-thickness ratio. However, the value of local maximum of von Misses stress remains unchanged. Also it can be concluded that the mode of buckling for flat-bar stiffened plate is a combination of web and plate buckling regardless of pit depth to plate thickness ratios. However, for tee-bar stiffened plates, mode of buckling changes with ratio of pit depth to plate thickness.

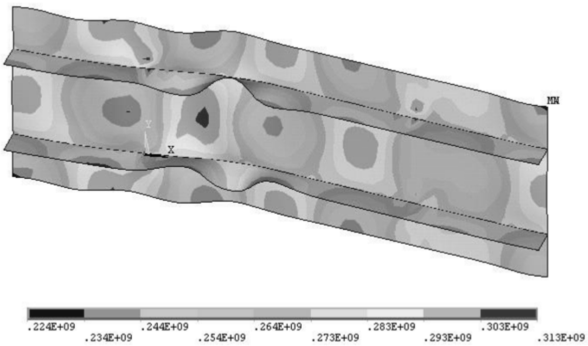




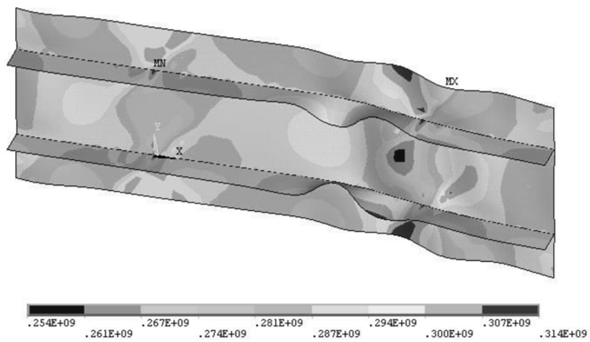
(a) No pit.



(b) Pit depth to thickness ratio, 25%.

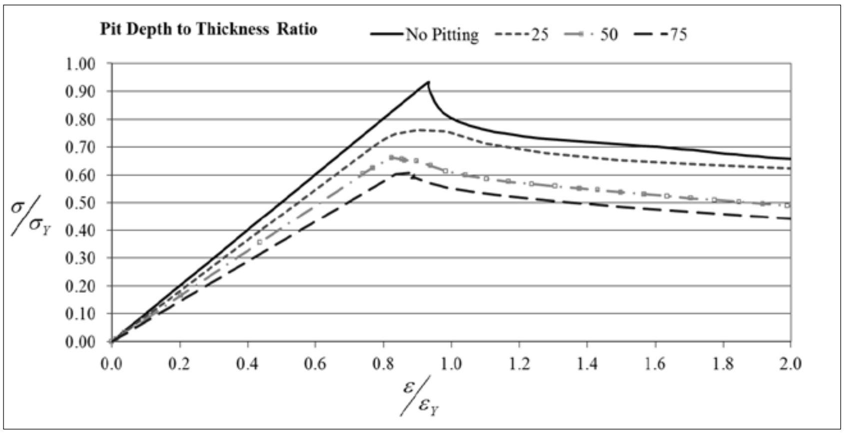


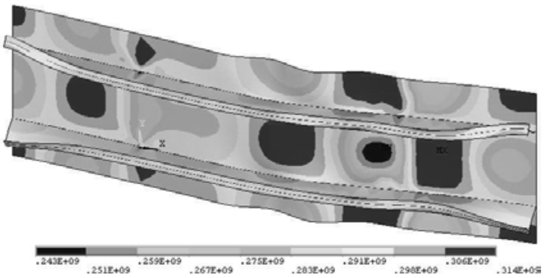
(c) Pit depth to thickness ratio, 50%.



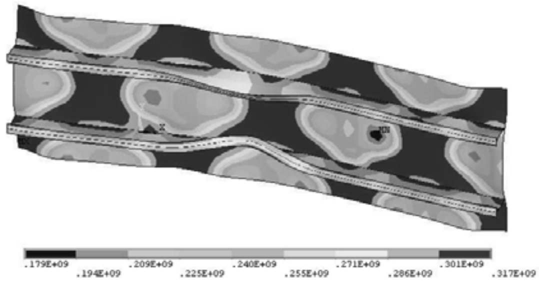
(d) Pit depth to thickness ratio, 75%.

Fig. 7 Stress-strain diagrams and von-Misses stress distribution, 15 *mm* plate, stiffener type F2, and DOP 50%.

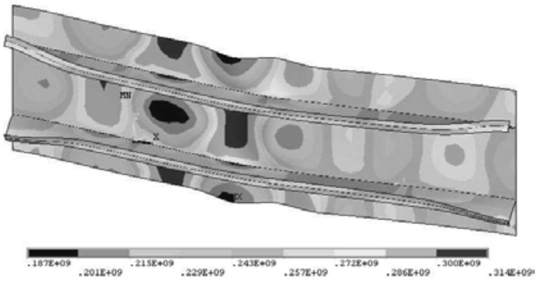




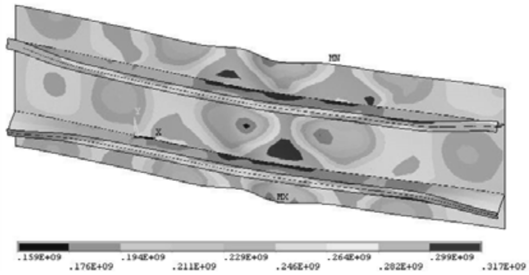
(a) No pit.



(b) Pit depth to thickness ratio, 25%.



(c) Pit depth to thickness ratio, 50%.



(d) Pit depth to thickness ratio, 75%.

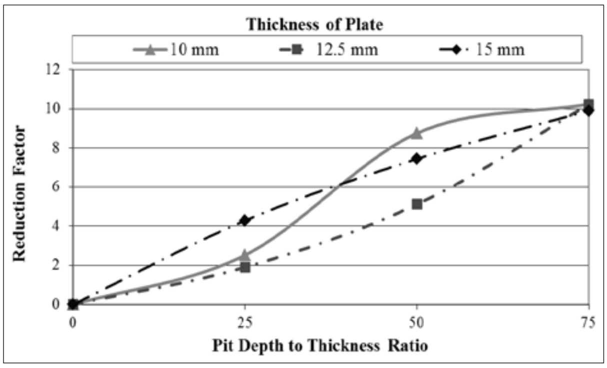
Fig. 8 Stress-strain diagrams and von-Misses stress distribution, 15 *mm* plate, stiffener type T2, and DOP 50%.

To study the influence of different parameters on reduction of ultimate strength, a new parameter is defined as follows:

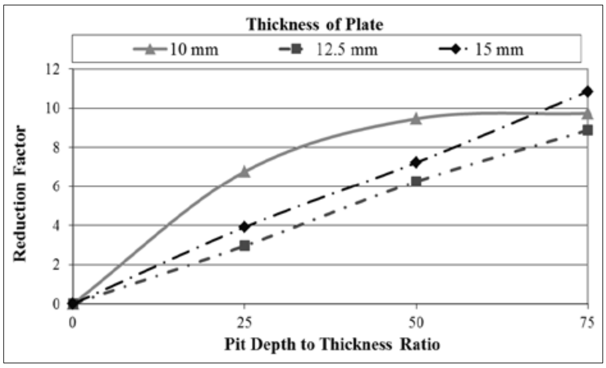
$$R = \frac{\text{Ultimate strength of uncorroded plate-Ultimate strength of pitted plate}}{\text{Ultimate strength of uncorroded plate}} \times 100$$

Figs. 9 to 10 depict reduction of ultimate strength of pitted stiffened plates as a function of depth-to-thickness ratio for DOP 6.25%, 12.5%, 25% and 50%, different plate thickness and type of stiffeners. As can be seen, regardless of shape and size of stiffener, thickness of plate and DOP, reduction factor increases by increasing ratio of pit depth to plate thickness. However, its influence is not the same for different thickness of plate. For example, maximum reduction of ultimate strength occurs in plate thickness 15 *mm* (intermediate plate thickness) and type 2 of stiffeners, when ratio of pit depth to thickness is less than 50%. Maximum reduction of ultimate strength in intermediate plate and type 1 of stiffener depends on DOP. Minimum reduction of ultimate strength occurs in plate thickness 10 *mm* (thin plate) and type 2 of stiffeners. Minimum reduction of ultimate strength in type 1 of stiffener and thin plate depends on DOP.

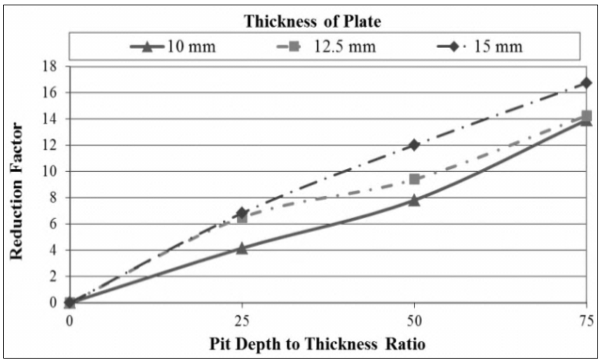
For DOP equal to 50%, reduction of ultimate strength of plate thickness 20 *mm* (thick plate) and thickness 10 *mm* are the same. For DOP less than 50% and pit depth to plate thickness higher than 50%, thick plate has maximum reduction of ultimate strength. Therefore, the behavior of thick plate strongly depends on DOP and ratio of pit depth over plate thickness.



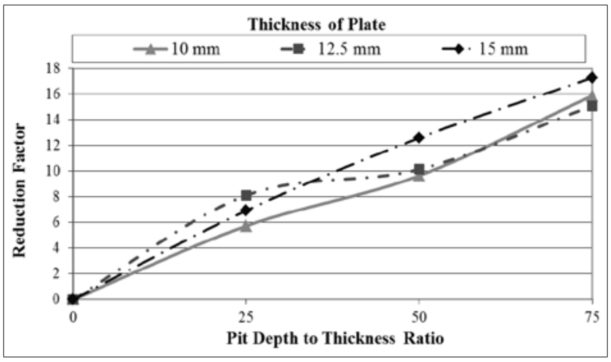
(a) DOP 6.25%, F1 stiffener.



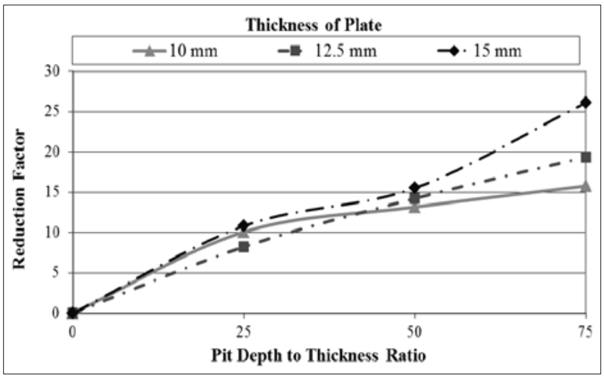
(b) DOP 6.25%, T1 stiffener.



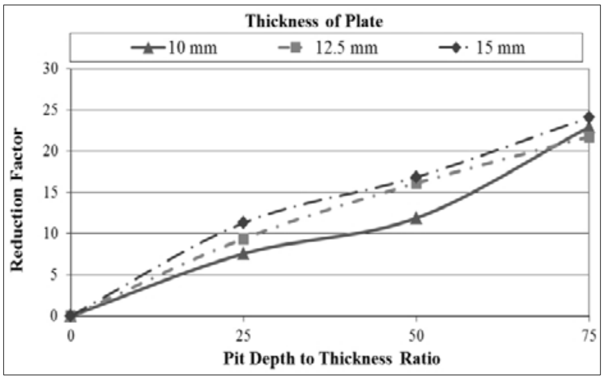
(c) DOP 12.5%, F1 stiffener.



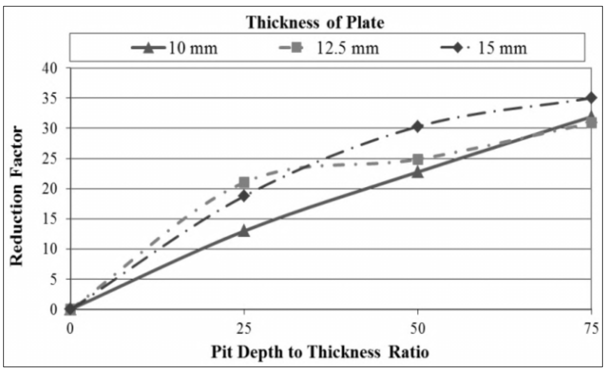
(d) DOP 12.5%, T1 stiffener.



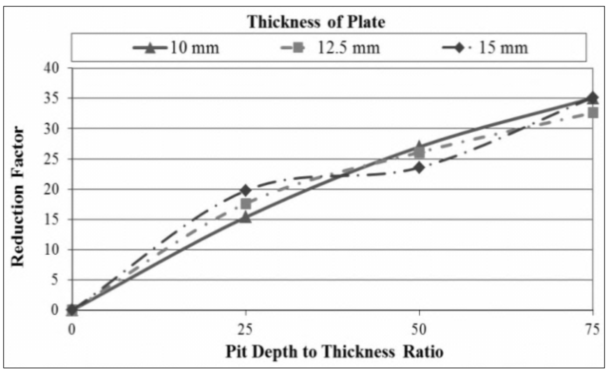
(e) DOP 25%, F1 stiffener.



(f) DOP 25%, T1 stiffener.

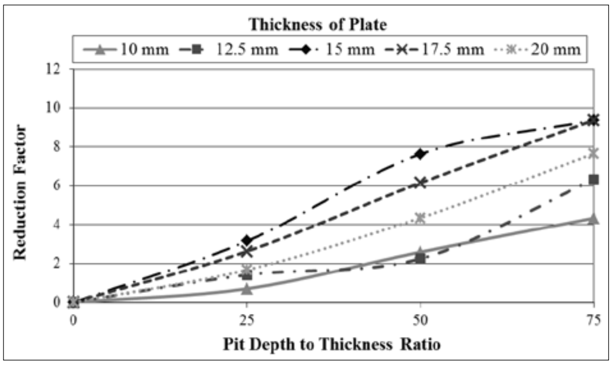


(g) DOP 50%, F1 stiffener.

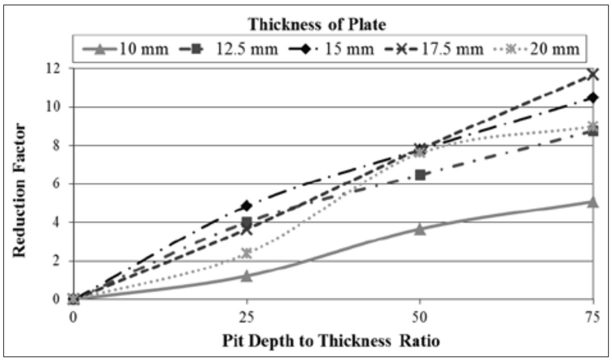


(h) DOP 50%, T1 stiffener.

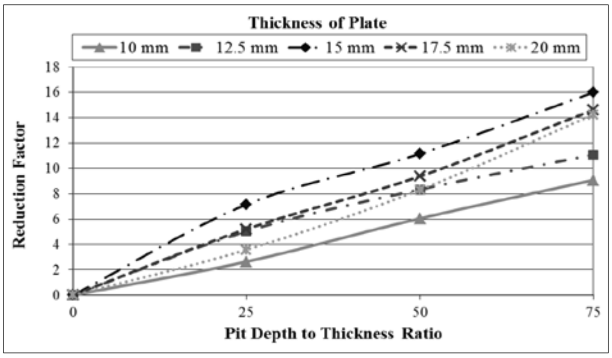
Fig. 9 Reduction factor in pitted stiffened plate, stiffener type 1.



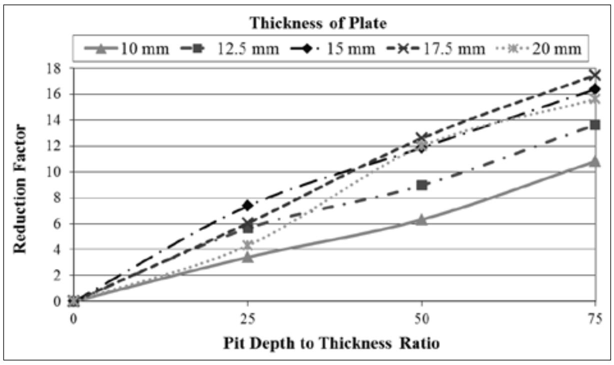
(a) DOP 6.25%, F2 stiffener.



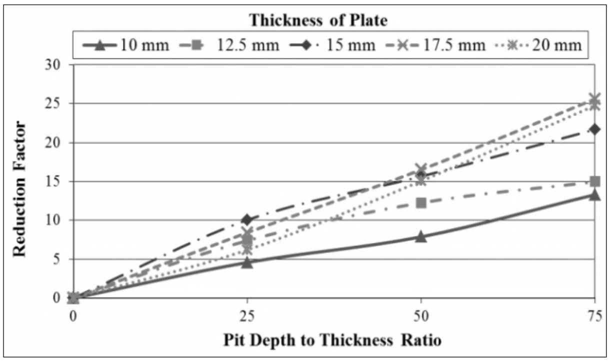
(b) DOP 6.25%, T2 stiffener.



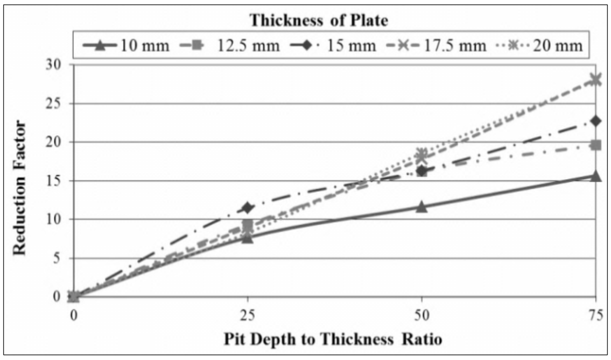
(c) DOP 12.5%, F2 stiffener.



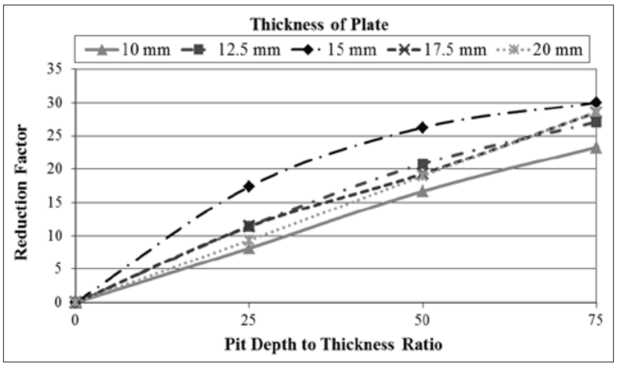
(d) DOP 12.5%, T2 stiffener.



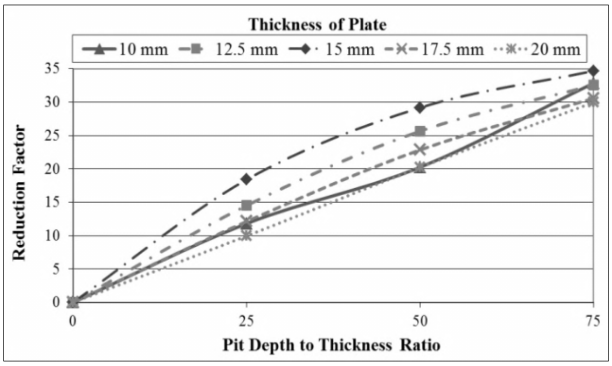
(e) DOP 25%, F2 stiffener.



(f) DOP 25%, T2 stiffener.



(g) DOP 50%, F2 stiffener.

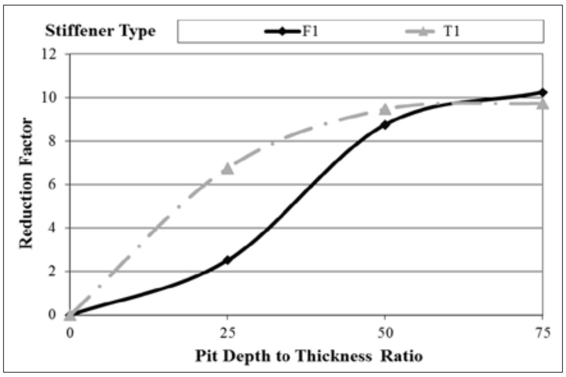


(h) DOP 50%, T2 stiffener.

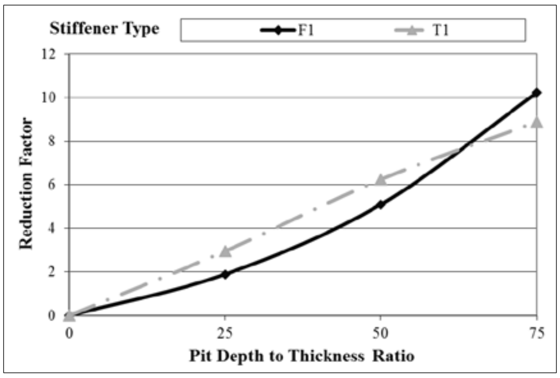
Fig. 10 Reduction factor in pitted stiffened plate, stiffener type 2.

In other words, pit depth to thickness ratio always has negative effect on reduction of ultimate strength, but the amount of reduction depends on thickness of plate, DOP and size of stiffener. Thin plates and intermediate plates have minimum and maximum values of reduction factor with stronger stiffeners, respectively. In weak stiffener, reduction of ultimate strength in thin and intermediate plates depends on DOP. Reduction factor in thick plates depends on thickness of plate and DOP.

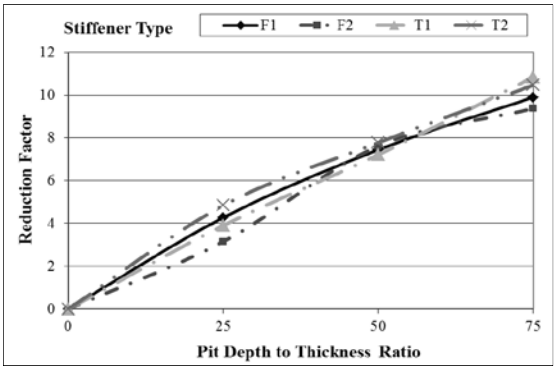
Figs. 11 to 14 depict reduction of ultimate strength of pitted stiffened plates as a function of pit depth to thickness ratio for DOP 6.25%, 12.5%, 25% and 50%, different thickness of plate and stiffener types 1 and 2. As can be seen, for thick plates (17.5 *mm* and 20 *mm*), reduction factor for tee-bar stiffeners is higher than flat-bar stiffeners. For intermediate plates (15 *mm*), reduction factor for all stiffeners regardless of shape and size are the same. For thin plates (10 *mm* and 12.5 *mm*), reduction factor for tee-bars is higher than flat-bars for small values of DOP (say up-to 12.5%), for higher values of DOP, reduction factor depends on thickness of plate and pit depth to thickness ratio. Therefore, shape and size of stiffener, and thickness of plate have influence on reduction of ultimate strength since, depending on relative thickness of plate, shape or size of stiffener, different mode of buckling and failure could occurs and detrimental effect of corrosion in different modes are not the same.



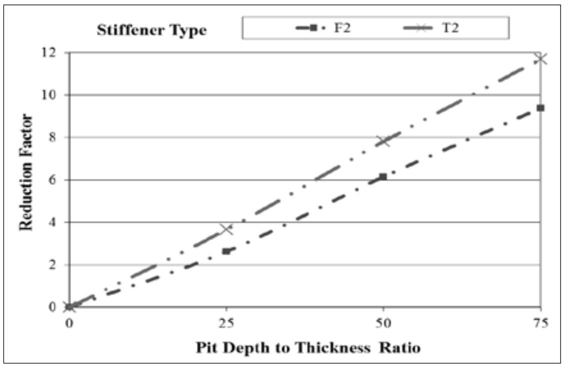
(a) Plate thickness 10 *mm*.



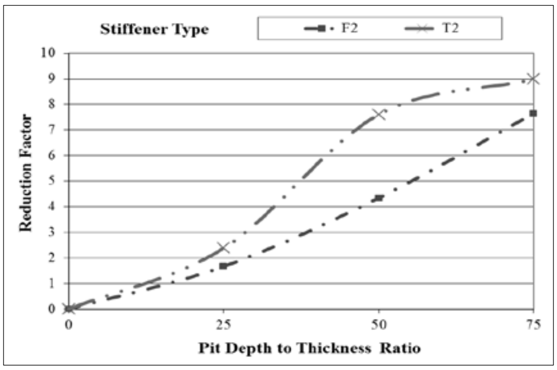
(b) Plate thickness 12.5 *mm*.



(c) Plate thickness 15 *mm*.

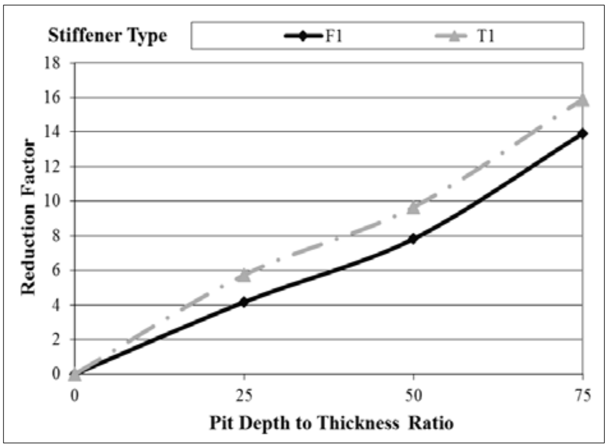


(d) Plate thickness 17.5 *mm*.

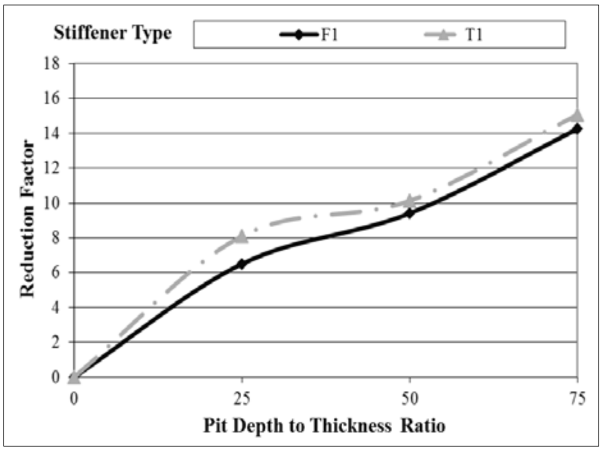


(e) Plate thickness 20 *mm*.

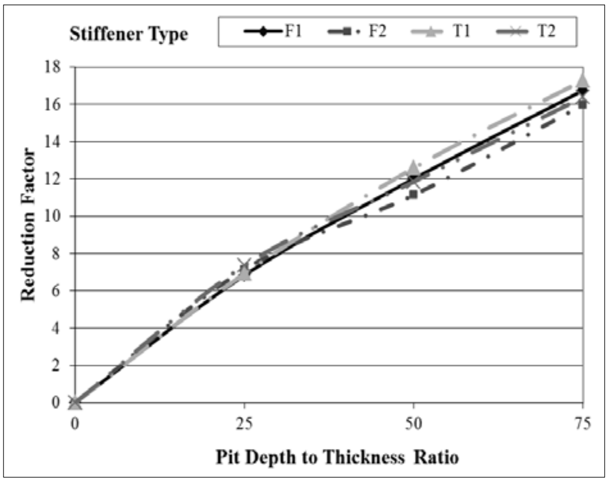
Fig. 11 Reduction factor of ultimate strength of pitted stiffened plates, DOP 6.25%.



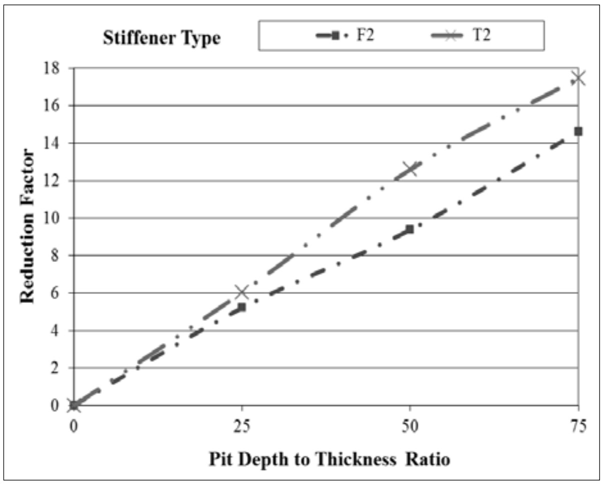
(a) Plate thickness 10 *mm*.



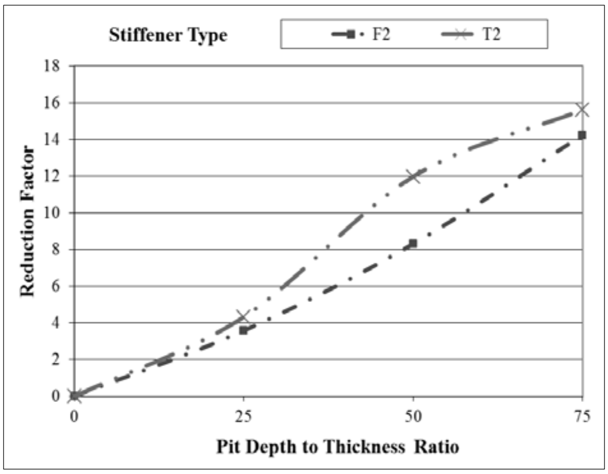
(b) Plate thickness 12.5 *mm.*



(c) Plate thickness 15 *mm.*

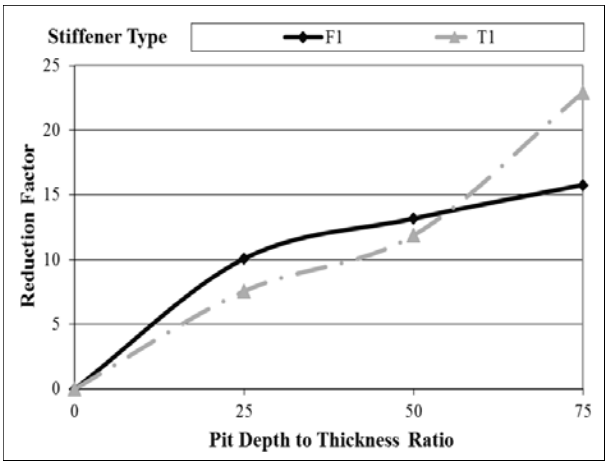


(d) Plate thickness 17.5 *mm.*

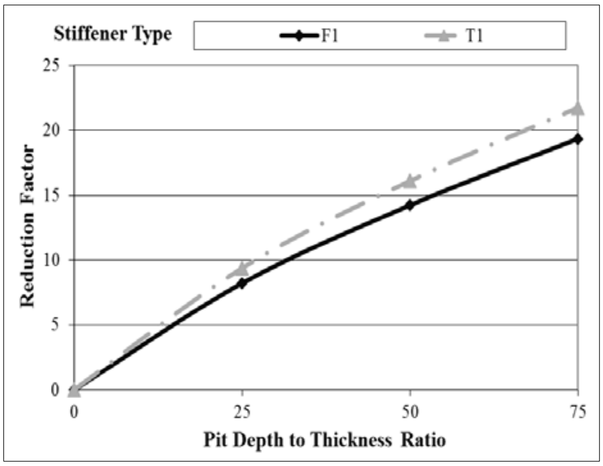


(e) Plate thickness 20 *mm.*

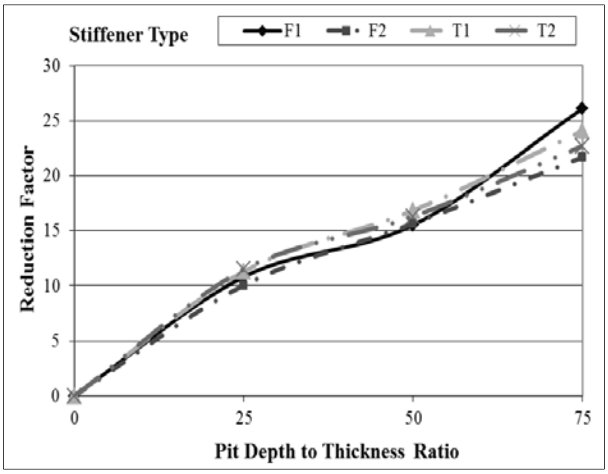
Fig. 12 Reduction factor of ultimate strength of pitted stiffened plates, DOP 12.5%.



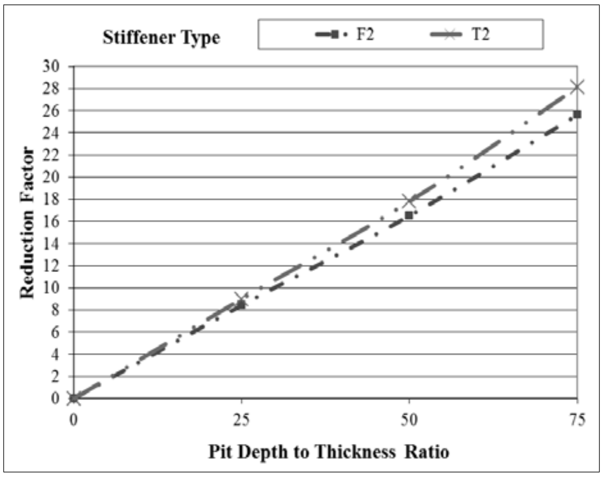
(a) Plate thickness 10 *mm*.



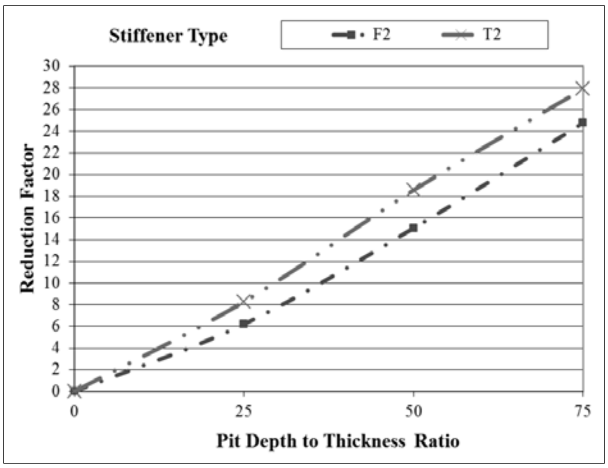
(b) Plate thickness 12.5 *mm.*



(c) Plate thickness 15 *mm.*

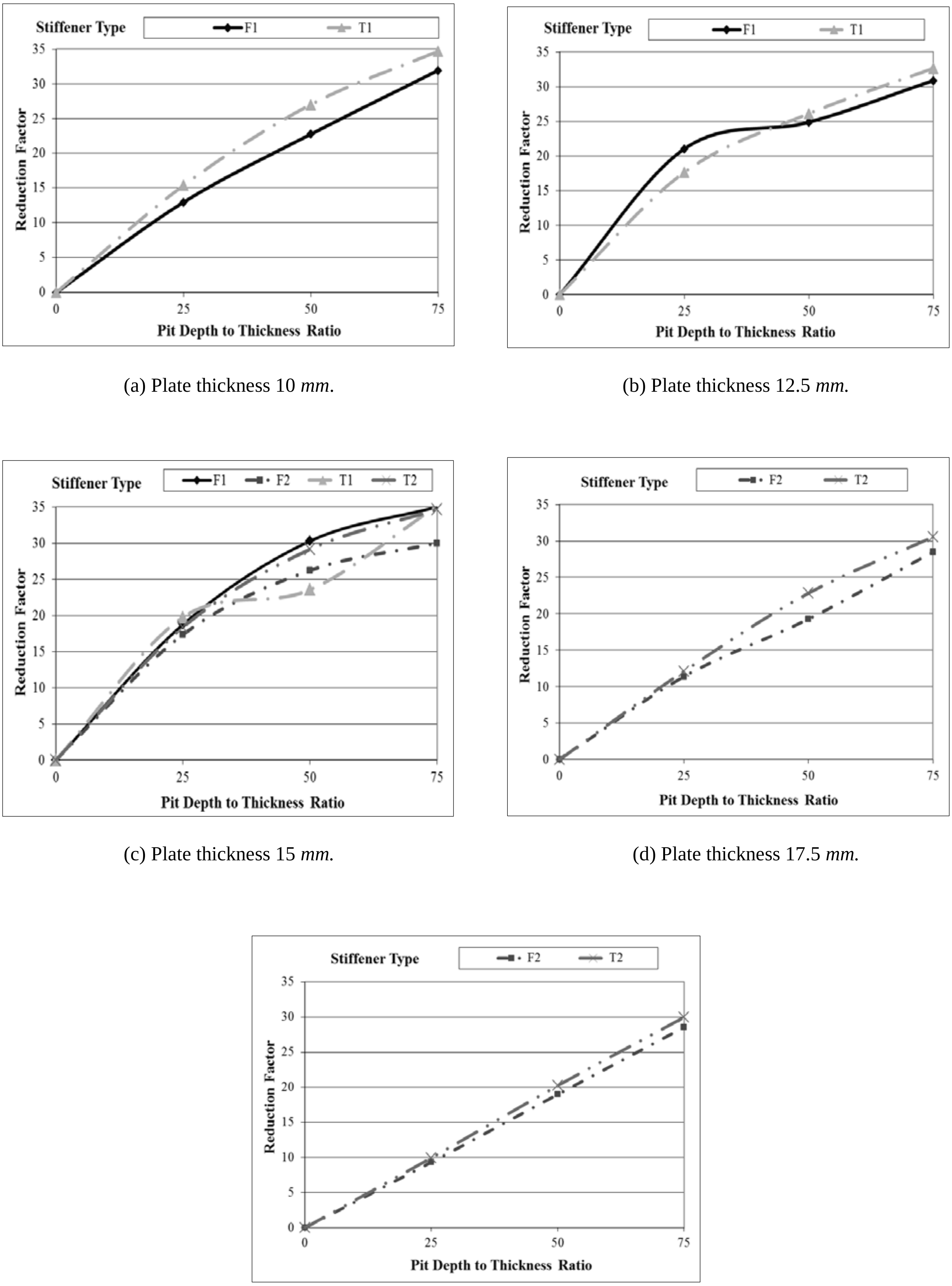


(d) Plate thickness 17.5 *mm.*



(e) Plate thickness 20 *mm.*

Fig. 13 Reduction factor of ultimate strength of pitted stiffened plates, DOP 25%.



(a) Plate thickness 10 *mm*.

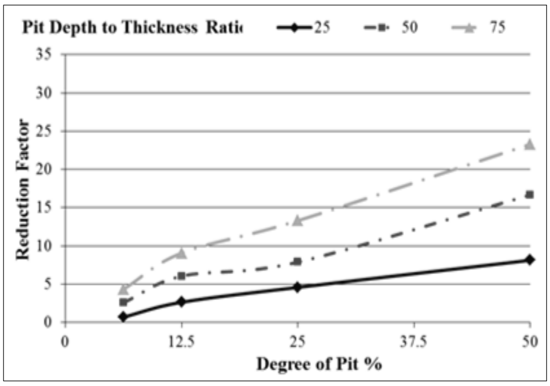
(b) Plate thickness 12.5 *mm*.

(c) Plate thickness 15 *mm*.

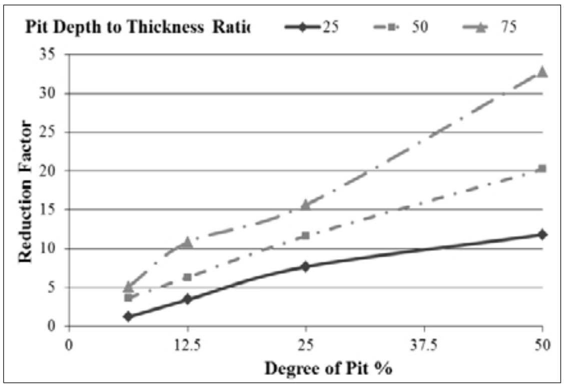
(d) Plate thickness 17.5 *mm*.

(e) Plate thickness 20 *mm*.

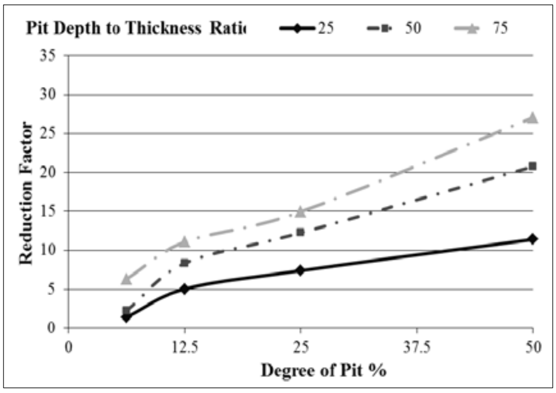
Fig. 14 Reduction factor of ultimate strength of pitted stiffened plates, DOP 50%.



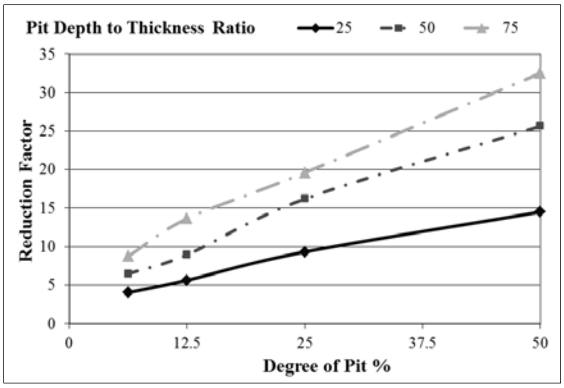
(a) t=10 *mm*, Stiffener F2.



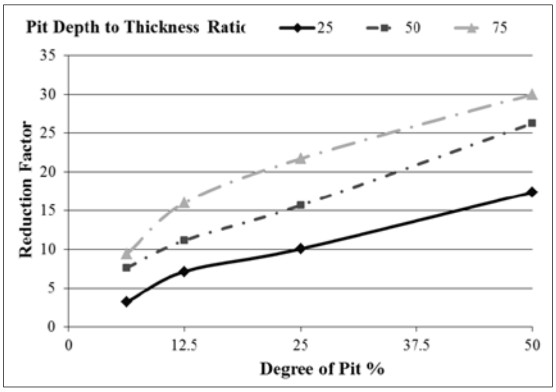
(b) t=10 *mm*, Stiffener T2.



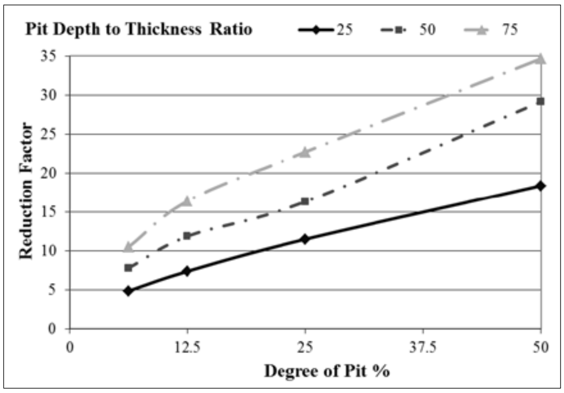
(c) t=12.5 *mm*, Stiffener F2.



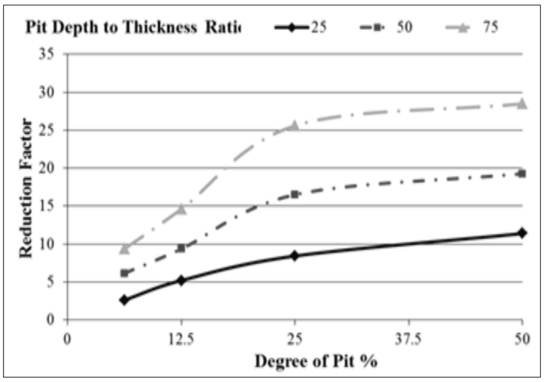
(d) t=12.5 *mm*, Stiffener T2.



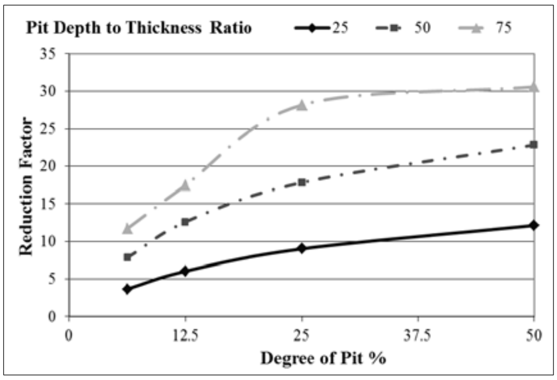
(e) t=15 *mm*, Stiffener F2.



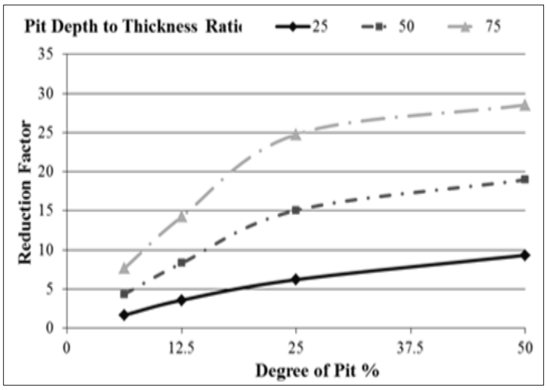
(f) t=15 *mm*, Stiffener T2.



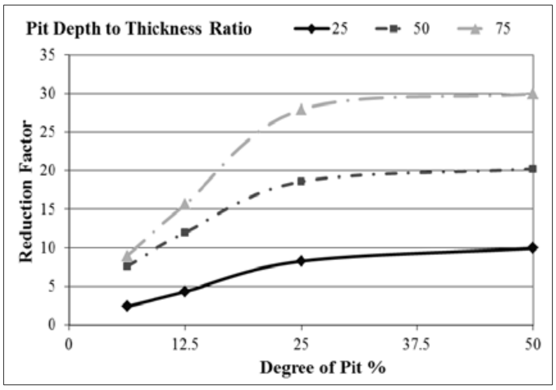
(g) t=17.5 *mm*, Stiffener F2.



(h) t=17.5 *mm*, Stiffener T2.



(i) t=20 *mm*, Stiffener F2.



(j) t=20 *mm*, Stiffener T2.

Fig. 15 Reduction factor of ultimate strength of pitted stiffened plates for different value of plate thickness, stiffener type and ratio of pit depth to plate thickness.

Fig. 15 shows the variation of reduction factor for different values of DOP, thickness of plate, shape of stiffener and pit depth to thickness ratio. It can be concluded that, DOP and pit depth to thickness ratio have increasing effect on ultimate strength reduction factor, regardless of shape and size of stiffeners. For thick plate, reduction factor increases by increasing DOP till 25%, and after that remains constant.

CONCLUSIONS

There is little study on strength reduction of pitted corroded stiffened plate. Nonlinear, large deflection finite element method with elastic-strain hardening material is used for ultimate strength calculation of one-sided pitted stiffened plates. A reduction factor is introduced as a ratio of reduction of ultimate strength of pitted stiffened plate over ultimate strength of un-corroded stiffened plate. Scope of this study covers assessment of influence of depth of pits, Degree of Pitting (DOP), types and size of stiffeners and thickness of plate on ultimate strength reduction of stiffened plate. It is found that, regardless of shape and size of stiffener, thickness of plate and DOP, reduction factor increases by increasing pit depth to thickness ratio. However, the amount of reduction of ultimate strength depends on thickness of plate. Thin plates and intermediate plates have minimum and maximum values of reduction factor with stronger stiffeners, respectively. In weak stiffener, reduction of ultimate strength in thin and intermediate plates depends on DOP. Reduction factor in thick plates depends on thickness of plate and DOP.

In thick plates, reduction factor for tee-bar stiffeners is higher than flat-bar stiffeners. For intermediate plates, reduction factor for all stiffeners regardless of shape and size are the same. For thin plates, reduction factor for tee-bars is higher than flat-bars for small values of DOP. For higher values of DOP, reduction factor depends on thickness of plate and pit depth to thickness ratio. For thick plate, reduction factor increases by increasing DOP till 25%, and after that remains constant.

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